Analytic Methods for Minimizing Hohlraum Wall Losses and the Problem of Oxygen Contamination

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We wish to minimize ICF hohlraum wall loss, E, in order to operate the National Ignition Facility (NIF) far from its damage threshold and still provide the capsule with the drive it requires to reach ignition. In this paper we consider cocktail walls- a mixture of materials that can improve on the conventional pure Au walls. We use Hammer & Rosen (HR) (2003) which solved the radiation diffusion / hydrodynamics problem analytically. We take Au's T, ρ dependencies of κ (opacity) and e (specific heat) to be:

$$\kappa = \kappa_0 \, \rho^{\,0.2} / T^{\,1.5} \quad \text{and} \quad e = e_0 T^{\,1.6} / \rho^{\,0.14} \quad (1)$$

We made a self-similar assumption $T=T_B t^k f(m/m_F(t))$ where m is a running integral of ρdx. We found to zero order, a spatial profile $f=(1-(m/m_F(t))^{1/4}$ where $m_F(t) =m_{F0}t^{(1+4k)/2}$, and we found the scaling:

$$m_F \sim \frac{T^{1.91}t^{.52}}{\left(\kappa_0 e_0\right)^{0.48}} \Rightarrow \frac{E}{A} \sim em_F \sim \frac{e_0^{\,0.7}}{\kappa_o^{\,0.4}} T^{3.34}t^{.6} \quad (2).$$

We also determined the exact coefficients for k = 0.18. m_{F0} =7.4 10^{-4} g/cm^2 and E/A=0.39 hJ/mm^2. The absorbed flux is given by $F=F_0 T^{3.34} t^{-0.41}$ with F_0=0.46 hJ/ns/mm^2 and E/A is simply the time integral of F. For k=0.18 remember to put the time dependence of $T = T_0 t^{0.18}$ into the equations. Thus for example the E/A (for k=0.18) = 0.39 $T_0^{\,3.34}$ $t^{\,1.2}$ hJ/mm^2.

We can now, predict the hohlraum temperature for a given hohlraum geometry and incident laser pulse. To calculate this analytically we adopt a simple "source=sink" model. The source is the laser energy E_L, converted to x-rays, so that now $\eta_{CE} E_L$ worth of x-rays bathe the hohlraum walls. We set that source equal to the energy sinks, which for a very simple hohlraum (no capsule) is the wall loss (E/A of Eq. (2) times the area of the walls), and the LEH loss which is the time integral of σT^4 times the area of the laser entrance holes. We use convenient "radiation hohlraum units" ("rhu") in which T is in hectovolts (hundreds of eV), area in mm^2, time in ns, mass in gm and energy in hectojoules. Then $\sigma = 1.03$ and normalized irradiance is 10^{13} W/cm^2 (= hJ/mm^2 ns = 10^2 J /10^{-2} cm^2 10^{-9} s) and normalized power is 10^{11}W (= hJ/ns = 10^2 J /10^{-9} s).

As an example we take our baseline Au hohlraum at the Omega Laser at URLLE which was a "scale 0.75" cylinder (L=2.06 mm, R=0.6 mm, with 66% LEH (R=0.4 mm)

so that $A_W = A_{end\ caps} + A_{cyl\ wall} = 1.2 + 7.8 = 9.0$ mm^2 and $A_{LEH} = 1$ mm^2. The incident flattop power was 20 TW for 1ns. We use k=0.18 because simulations predict a $\eta_{CE} = 0.7\ t_{ns}^{0.2}$. Equating $\eta_{CE}\ E_L = \eta_{CE}\ P_L t$ which scales as t$^{1.2}$ to the principal x-ray sink, the wall, E_W which scales as $T^{3.3}t^{0.6}$ (Eq. (2)) we see that these two terms will balance iff $T = T_0 t^{0.18}$ We see 8% reflectivity, so with a 68% conversion efficiency we get a source at 1 ns of 101 hJ. We set that equal to the wall loss $3.5T_0^{3.3}$ and LEH loss $0.6T_0^4$, solve for T and get T=2.55 with 76 hJ wall loss and 25 LEH loss. This 255 eV is very close to the data.

When we consider Eq. (2) we see that in order to lower the E/A of a wall loss, we need to lower e and to raise k. Since e scales as Z/A the higher the A the lower (at a given T) will be the ionization state Z and hence e. Thus mixing in higher A elements into the wall will lower e. Moreover, if we do mix in a higher A element, at a given T, it will have different atomic levels and thus its opacity, if A is chosen properly, will be high at frequencies where Au's is low. Thus this "cocktail" of materials can accomplish both things. Experiments with cocktails (Orzechowski (1996)) compared the burn-through times t_{bt} of Au foils placed across a hole in the side of a 260 eV hohlraum, to those of AuGd cocktail foils. A delay in burn-through signal for the cocktail was seen. By Eq. (2) we expect (again for a k=0.18 case) that t_{bt} should scale as $mT_0^{-2}(e\kappa)^{1/2}$, so the higher κ of the AuGd cocktail caused the delay. Since then we have tried to measure the rise in T for a full cocktail (vs. Au) hohlraum at the same laser drive. The cocktail chosen was $U_{0.6}Dy_{0.2}Au_{0.2}$ which at NIF-like temperatures of 300 eV can save nearly 20% in wall loss.

We fit our latest opacity/ EOS theory of Au as $\kappa = 6544\ \rho^{0.18}/T^{1.43}$ (cm^2/g) and e = $3.33\ T^{1.54}/\rho^{0.15}$ (MJ/g), and of $U_{0.6}Dy_{0.2}Au_{0.2}$ as $\kappa = 5670\ \rho^{0.10}/T^{0.90}$ (cm^2/g) and e = 0.95 e_{Au}. The cocktail has a "flatter", less sensitive T, ρ behaviour because it averages over several elements. We also note that the opacity of cocktails does not exceed that of Au until past 130 eV. Using that input, HR predicts for k=0.18, for Au an E/A =0.398 $T^{3.3}t^{0.6}$ (hJ/mm^2) and for $U_{0.6}Dy_{0.2}Au_{0.2}$, E/A = 0.407 $T^{3.1}t^{0.57}$ (hJ/mm^2). Thus, at 270 eV and 1 ns, the wall loss ratio (cocktail/Au) is 0.85 while a full multi-group simulation gives 0.87, very close to HR theory but differing mostly because the opacity is hard to fit with a single power law. U mixed with 6% Nb by weight (=14 atom %) adds 1% to these ratios.

Another outgrowth of these scaling laws is to notice that the wall loss ratio scales as $T^{-0.22}\ t^{-0.05}$. Thus to the degree that the Omega experiments are not either at the full NIF temperature of 300 eV, nor at the NIF pulse length of 3-4 ns, then the results from such

experiments will be pessimistic in showing a wall loss ratio advantage of a cocktail hohlraum over Au than would a NIF ignition hohlraum. (The ratio for NIF is about 0.83). These time behaviours stem from the fact that early in time the lower T parts of the Marshak profile are relatively more important, and for low T cocktail is worse than Au.

So let us redo the Omega hohlraum calculation for T with cocktail walls (actually shot with $U_{0.86}Nb_{0.14}$) and thus our E/A wall loss is 0.416 T $^{3.1}$ at 1 ns vs. Au 0.39 T $^{3.3}$. The solution now to 101 = 3.7 T $^{3.1}$ + 0.6 T^4 is T=2.62 so we expect a 7 eV hotter hohlraum than the 255 eV Au hohlraum. Many shots were done with Au end plates and just a cylinder body of cocktail. Redoing that we must solve 101= 0.49T $^{3.3}$ + 3.2 T $^{3.1}$ + 0.6T^4 we get 2.61 thus we expect a 6 eV improvement for those type of cocktail hohlraums. However, until very recently there was only a 2.5 eV difference between Au and cocktail hohlraums. We believe this is due to oxygen contaminating the cocktail walls in the process of making them. Since cocktail foils don't necessarily get leached from their substrates, cocktails hohlraums certainly do and the leaching process may be the key to the contamination. While Au does not bind to O, U & Dy certainly do – they are in fact often used as O getters! The trouble with O in the cocktail is that they are fully ionized so contribute about twice the Z per unit weight than the high Z elements, and thus raise e by raising the specific heat.

For atomic numbers between 6 and 71 and for T between 1 & 3 heV we find the following fits for the specific energy e. The ideal gas law would give e_{ig} = 15 [(Z+1)/A] T_{heV} in MJ/g. Here the ionization state Z is fit by $Z = (Z_N/71)^{0.6}$ 16 T_{heV} $^{0.6}$ / $\rho_{g/cc}$ $^{0.14}$. There are non-ideal gas law contributions, principally from ionization energy, and we fit those by a multiplier "mult" = 2.5 $(Z_N/71)^{0.1}$. Thus e = (e_{ig}) ("mult") which we can write as δ_N/A_N. The reader can check that this gives a number reasonably close to the one we quoted for Au above. For a mixture of j elements we take the ratio e= Σ δ_{Nj} / Σ A_{Nj}. (not, Σ (δ_{Nj} / A_{Nj})). So for example for a AuNdDy cocktail to be discussed shortly, we find e_c/e_{Au} = 1.06 with no oxygen, 1.08 with 4% O, and 1.22 with 40% O.

A vivid example of the O problem came from a re-analysis of another burn-through experiment, that of Olsen et. al. (2003). A AuNdDy cocktail foil burn-through time (t $_{b.t.c}$) was compared to that of an Au foil's in a 160 eV hohlraum with a T that rose as t $^{0.1}$. This would lead us to predict that (via the equivalent of Eq. (2)) the ratio of $(\kappa e)_c/(\kappa e)_{Au}$ would equal $[(\rho\Delta x)_{Au}/(\rho\Delta x)_c]]^{2.08}$ times [t $_{b.t.c}$/t $_{b.t.Au}]^{1.5}$. Plugging in the data that

equals $[1.9 / 1.5]^{2.08}$ times $[1.3 \text{ ns} / 1.45 \text{ ns}]^{1.5} = 1.38$. Now theoretically the $(\kappa e)_c/(\kappa e)_{Au}$ ratio should be 1.22 which disagrees with the data. But if there were an O for each Dy and for each Nd, then theoretically the ratio is 1.36 quite close (and well within error bars) of the data. Thus due to this re-analysis, we "post-dicted" that the sample was fully oxygenated. We then had the target fabrication records examined and indeed that was precisely the case! Of course, future targets should be carefully made without O.

Assuming the past cocktail hohlraums were indeed fully oxygenated we can redo our source=sink model once again but with a lossier wall loss due to the high e due to the oxygen. Now the E/A coefficient is 0.44 and, with Au end plates we solve $101 = 0.49 \text{ T}^{3.3} + 3.4 \text{ T}^{3.1} + 0.6 \text{ T}^{4}$ and get T = 2.575, a 2.5 eV difference from the 255 eV pure Au hohlraums, in rather close agreement with what was observed. The good news is that very recent shots in which great care has been taken to avoid oxygenation, has shown the cocktail hohlraums about 6 eV hotter than the Au ones, as expected.

References

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